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Development of Bi-2212 insert coils for ultra high field magnet applications

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Abstract

Ultra high field magnets for research applications require development of insert coils developed from high temperature superconductor materials (HTS) like Bi-2212 round wires. Integration of an outer, wide bore, magnet fabricated from low temperature superconductor materials (LTS) coils with insert HTS coils will entail understanding of the quench behavior of the combined system and crucial for the safe energization and operation of compact high field magnets where quench management of LTS differ for those of HTS coils. In the present study, the quench behavior of the HTS coils and the LTS coils used to provide the background field were measured and analyzed. The analysis is highly relevant to the design of high field wide bore magnets as well as ultra high field magnets using integrated LTS and HTS coils.

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1. Introduction

The increasing availability of high field (HF) superconducting magnets has led to many advances in varied fields of science and technology. Demand for fields above 25T has in turn driven advances in the development of HTS insert coils. This is because currently available LTS materials cannot produce a field much higher than 21T at 4.2k or 23.5T at 2K. HTS materials, such as Bi-2212 round wire and the YBCO

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tapes, have been demonstrated to have an upper critical field in excess of 30T. For this reason, such materials will be vital in the continued development of ultra high field magnets.

The need for combined LTS and HTS magnets requires a design tool able to model the interactions between coils of both types. This need led to the IMPDAHMA collaboration between Oxford Instruments Nanoscience, Cobham Technical Services Vector Fields Software and Southampton University. The aim of the collaboration was to develop a new software module for Vector Fields Opera which could perform a quench analysis of combined HTS and LTS magnets. The project involved the development of a high field wide bore LTS magnet designed to run at 20T contain HTS insert coils up to 2.5T. A series of Bi-2212 insert coils were tested, including a concentric pair of 6 layers, 300mm long coils. This is the configuration that we will turn our attention to here. In this work we selected the Bi-2212 round wire for our first batch of HTS inserts. This is to exploit their isotropic characteristic and permit the use of standard magnet engineering techniques in manufacturing and integrating HTS inserts with LTS coils.

The minimum quench energy (MQE) of a coil is, for a specific configuration of the coil (coil currents, background field, quench heater location etc.), the minimum thermal energy that needs to be applied to cause the coil to quench. During the IMPDAHMA project the MQE of the HTS inserts was investigated.

2. Minimum quench energy

A series of models were completed in an attempt to replicate the MQE behavior recorded in quench measurements of the HTS insert coils. The model initial boundary conditions were determined by matching the quench energies for the lowest and highest HTS currents with the measured data. The same assumptions were then used for all other MQE models.

In the IMPDAHMA study the HTS quench was initiated by a constantan ribbon heater applied around the ‘waist’ of the coil. A 0.02 second voltage pulse was applied in order to heat the superconducting coil. In the models this is approximated as a narrow area of heat flux on the outer surface f the HTS occurring as a linear fall-off in heat flux between 0s and 0.02s after the start of the model.

To determine the MQE values, models were run and analyzed to determine whether a quench occurred. The energy was then adjusted up or down accordingly and another model run to try to find the minimum energy of a quench. For each HTS current we then end up with two figures – a maximum energy without a quench event and a minimum energy with a quench event. The MQE was recorded as the midpoint of these two figures.

Table 1, Minimum quench energy model results

Case	LTS field (T)	HTS current (A)	MQE (mJ)
1	20	200	358
2	20	230	287.5
3	20	250	243.1
4	20	266	217

The results of the MQE study are shown in Table 1. The results of the models are in agreement with the measurements. A comparison of the two sets of data is shown in Fig 1a and Fig1b. The error bars on the model data in this figure indicate the energy of the highest energy model that did not quench and of the lowest energy model that did quench. The MQE is assumed to be the mean of the two.

The currents and voltages of individual coils are recorded in the model. This allows us to compare these quantities for models on either side of the minimum quench energy. Figs 2(a) and 2(b) show the voltages and currents from two models; one just above the MQE threshold and one just below. HTS1 is the inner of the two HTS coils and HTS2 is the outer. The behavior in the two cases is initially almost identical between the two models but the values diverge very rapidly at 0.1 seconds. The current and voltage rapidly re-converge on their initial values in the below MQE model. In the above MQE model they begin to re-converge before the quench takes over and they diverge rapidly. After 1 second (the full duration of the model, not shown) the currents in the inner and outer quenched coils are 189.4A and 92.4A respectively.

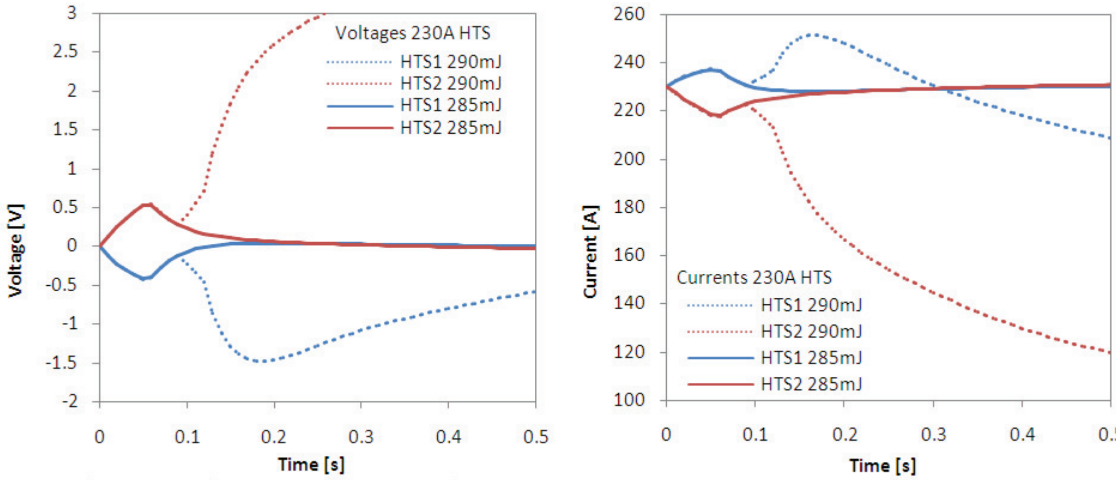

Fig. 1, (a) the voltages of models just below and just above MQE, (b) the currents of the same two models

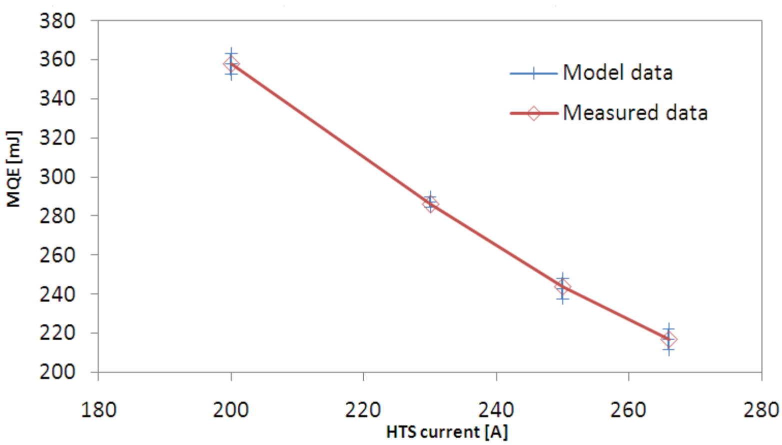

Fig. 2, a plot of MQE against the HTS current for the models and for measured value

The temperature distribution seen in the model with HTS current of 230A and heat flux of 311mJ is shown in Fig.3. The coils are zoomed in to show just the region of interest. Fig.3(a) shows the temperature distribution in the HTS coils 0.05s after the start of the model. Fig.3(b) shows the same model after 1s. The peak temperature seen in the one second that the model was allowed to run is 113K. The quench propagation velocity is very slow in this material and the quench does not propagate from the outer coil to the inner.

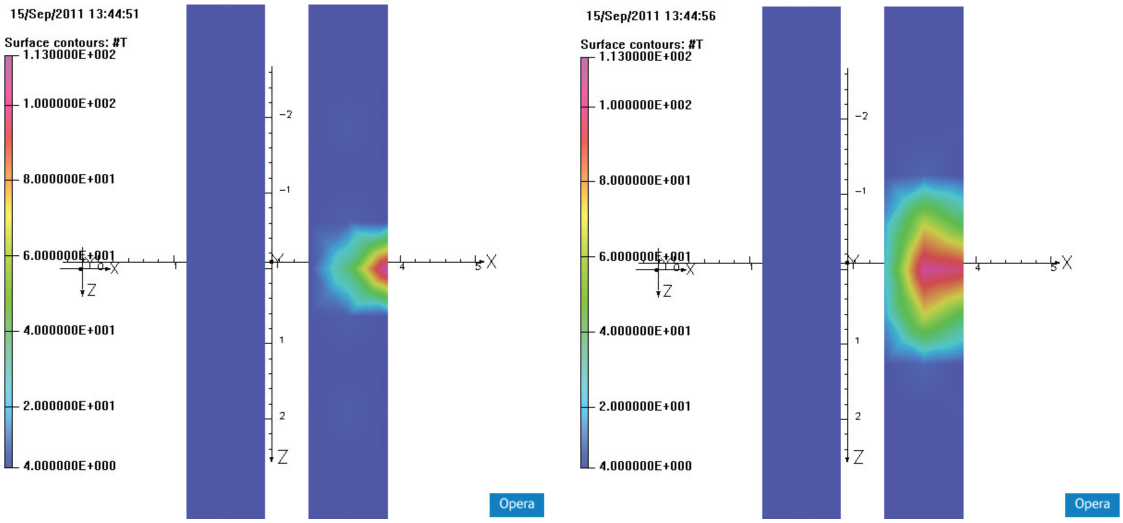

Fig. 4, temperature distribution in a 230A, 311mJ model after (a) 0.05s, (b) 1s

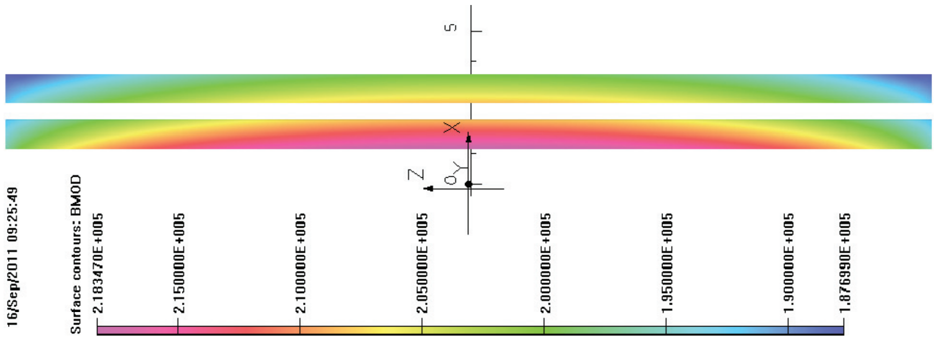

Fig. 5, magnetic field distribution in a 230A, 311mJ model after 0.05s

Fig. 5 shows the magnetic field distribution on the HTS coils after the first 0.05s of the same model. The peak field on the coils is 21.83T and is found at z=0 on the inner surface of the inner HTS coil. The peak field on the outer HTS coil is 20.85T.

In the 266A models above MQE the inner HTS coil does begin to quench after 0.1s. This is due to the increased current induced in the coil by the quench of the outer HTS, similar to what is seen in the 230A case in Fig. 1(b). In the region where the field is maximum there must be a region where the current goes above the critical current.

3. LTS and HTS combined system

We now present a model of the quench of the full LTS and HTS combined system. In this model the LTS coils are energized to 20T and the HTS coils have a current of 250A. The HTS and LTS coils run on separate circuits. The quench is initiated by a heat flux on the outer surface of the end of the outermost-but-one coil (shown in red in Fig. 6(a)). The temperature distribution is show in Figs. 5(a)-(d). The quench takes several seconds to take hold in the LTS but once it has propagated beyond the heated coil it quickly reaches all the other coils in the model. The maximum temperature reached after 5s is 267K and is seen in the outer HTS layer. This model illustrates that at this HTS current (which is only around 75% of the critical current) a quench of the LTS layers is enough to cause a HTS quench. Not only that, but the HTS rapidly becomes the hot spot of the system.

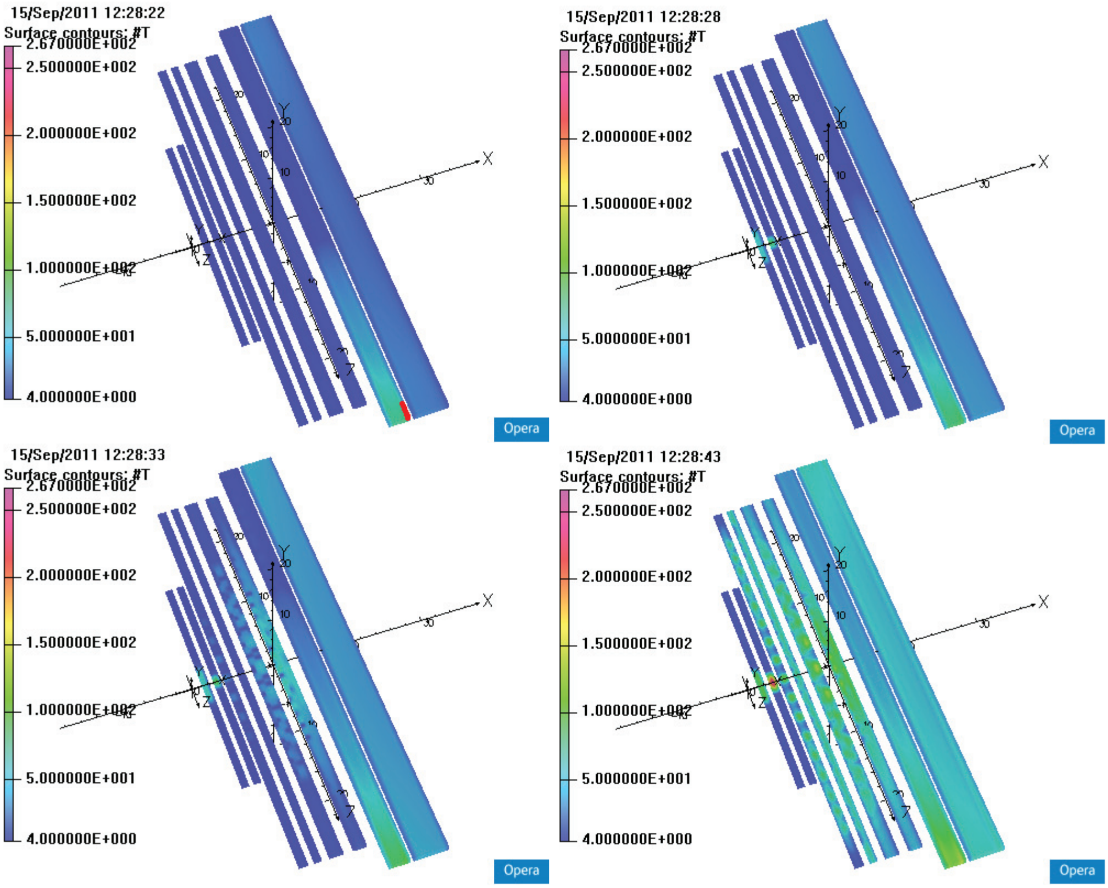

Fig. 6, The full LTS and HTS quench after (a) 2.5s , (b) 3s , (c) 3.5s, (d) 4s

4. Conclusion

Recent advances in Bi-2212 round wire allowed the development of insert coils for high field applications. The successful integration of a 2.5T Bi-2212 coil in a wide bore 20T LTS outsert operating at 4.2K enabled the testing of insert coils at 22.5T in a fully superconducting environment and provided a wealth of data on characteristics of HTS and LTS coils. The software module can reproduce the minimum quench energies measured in the real HTS inserts. The models also make realistic predictions of many other aspects of the quench behavior of HTS insert coils and of combined LTS and HTS systems. The slow quench propagation velocity observed in the HTS models could lead to localized high temperatures in the Bi-2212 in the event of a quench, leading to damage. There is therefore a need for carefully designed quench management schemes for coils of this material in order to quench the coil safely in the event of a quench..This kind of analysis is vital for the design and development of ultra high field superconducting magnets and will facilitate development of superconducting magnets greater than 25T where the successful integrations of LTS and HTS coils is vital. The analysis software will assist in the design of such a system by allowing us to predict the currents, voltages and temperatures in the coils. This will help by allowing us to work out how to detect a quench and how to safely quench the system if a quench is detected.

Research into higher performance BSCCO wire and YBCO tapes continues and it is hoped that this will lead to further enhancements in the highest fields attainable with these materials.

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